Discrete Optimization

Incorporating ergonomic risks into assembly line balancing

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A R T I C L E   I N F O
Article history:
Received 23 October 2010
Accepted 29 January 2011
Available online 4 February 2011

Keywords:
Scheduling
Combinatorial optimization
Ergonomic risk assessment
Assembly line balancing
Simulated annealing

A B S T R A C T
In manufacturing, control of ergonomic risks at manual workplaces is a necessity commanded by legisla-
tion, care for health of workers and economic considerations. Methods for estimating ergonomic risks of
workplaces are integrated into production routines at most firms that use the assembly-type of produc-
tion. Assembly line re-balancing, i.e., re-assignment of tasks to workers, is an effective and, in case that no
additional workstations are required, inexpensive method to reduce ergonomic risks. In our article, we
show that even though most ergonomic risk estimation methods involve nonlinear functions, they can
be integrated into assembly line balancing techniques at low additional computational cost. Our computa-
tional experiments indicate that re-balancing often leads to a substantial mitigation of ergonomic risks.

1. Introduction

The problem of unfavorable working conditions, or poor work-
place ergonomics, is an acute topic today. Ergonomic risks at the
workplace cause a lot of damage on health and quality of life of
workers, deteriorate economic results of employers and of the
economy as a whole. In 2008, along 315,000 cases of work-related
musculoskeletal disorders (MSDs, often referred to as ergonomic
injuries), requiring a median of 10 days away from work, were re-
ported in the US (Bureau of Labor Statistics, 2009). Annual com-
compensation cost for MSDs paid by employers in the US amount
to 15 to 20 billion US dollars. Moreover, occupational diseases of
workers indirectly cause further cost on firms: via loss of produc-
tion capacity due to absenteeism of workers, lower worker produc-
tivity and higher defect rates in work. This can be illustrated by
the example of Peugeot, whose ergonomics program reduced the cycle
time for the final vehicle assembly line together with a simulta-
nous decrease by 30% in new cases of musculoskeletal disorders
(Moreau, 2003).

Workplace ergonomics is becoming even more important fol-
lowing recent developments in legislation (EU Machinery directive,
2006/42/EC, 89/391/EEC, Occupational Safety and Health act of
1970 among others) and an on-going ageing of the workforce in
most of the developed countries.

Already today in assembly line production, especially in final
assembly, where the share of manual labor is high, a special atten-
tion is paid to ergonomics. Most renowned companies incorporate

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0377-2217/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ejor.2011.01.056
two-stage heuristic approach, furthermore, allows for a controllable increase in manufacturing capacity considering the trade-off between increased costs from adding stations on the one hand and reduced ergonomic risks on the other hand.

We precede with an overview of ergonomics tools in Section 2. A line balancing problem incorporating ergonomic risk factors, ErgoSALBP, is described and modeled in Section 3. In Section 4, we propose a two-stage heuristic, which is tested in comprehensive computational experiments in Section 5. A discussion in Section 6 concludes the paper.

2. Methods for estimating ergonomic risks

In the mandatory Appendix D.1 to §1910.900 of “Final Ergonomics Program Standard”, the Occupational Safety and Health Administration (2000; OSHA for short) provides a list of methods recommended for the estimation of ergonomic risks of workplaces. In this section, we provide a brief description of selected methods recommended by OSHA for application in assembly line production – the revised NIOSH (the National Institute for Occupational Safety and Health) equation and the job strain index; the method OCRA (Occupational Repetitive Action) recommended by European Norms on repetitive actions (EN 1005-5, 2007) and the EAWS (European Assembly Worksheet) method, which was created for and adapted by several European firms that employ an assembly production system.

Throughout the paper, we will use an example of an assembly line, the precedence graph for which is given in Fig. 1. The graph consists of \( n = 11 \) tasks \( i = 1, \ldots, n \) with task times \( t_i \) to be executed on each workpiece at a workstation during the cycle time of \( c = 63 \) seconds. Every task involves several actions of upper limbs, while some of them demand application of forces (see Table 1).

2.1. Risk estimation for manual handling: revised NIOSH equation

The NIOSH equation was developed in 1981 by the National Institute for Occupational Safety and Health for risk estimation of working conditions, where manual handling activities are the main source of risk and lifting comprises more than 90% of manual handling activities (Waters et al., 1994).

The NIOSH equation communicates a lifting index \( LI \) that shows the relation of the current load weight to the recommended load weight limit:

\[
LI = \frac{\text{Load weight}}{\text{Recommended weight limit}} \quad (1)
\]

The higher the lifting index, the higher percentage of the workforce is likely to be under risk for developing low back pain. The recommended weight limit is calculated depending on lifting conditions \( TS \), e.g. vertical travel distance of hands or degree of asymmetry in posture, and the frequency of lifting \( FM \):

Recommended weight limit = \( TS \cdot FM \) \quad (2)

The frequency multiplier \( FM \) is calculated based on the average number of lifts per minute. It takes into account the duration of the lifting activity, as well as the vertical height of the lift from the floor. In Table 2, we present frequency multipliers for 2–8 hours of continuous lifting and vertical lift height of 30 cm or more. \( TS \) considers task specific parameters and indicates the maximal recommended weight of the load that can be lifted by healthy workers under certain lifting conditions. For example, under the ergonomically most favorable lifting conditions (e.g. when the weight is held close to the body), \( TS \) is equal to 23 kg.

In our example, let us assume that tasks 6 and 7 are performed on the same station. The worker lifts – under ergonomically favorable lifting conditions – a 17 kg and a 15 kg load in each cycle of 63 seconds (see Table 1). The task specific parameter \( TS \) for both cases of lifting has the ideal value of 23 kg and the frequency multiplier \( FM \) for both cases is 0.7557 (60/63 = 0.9524 lifts per minute, the value of \( FM \) is retrieved from Table 2 by interpolation). So, the recommended weight limit is 17.38 kg and the resulting lifting indices are 0.98 for task 6 and 0.86 for task 7.

In case of several lifting tasks, we compute the composite lifting index \( CLI \) as follows:

\[
CLI = LI_1 + \left( LI_{12}^2 - LI_1^2 \right) + \left( LI_{123}^2 - LI_{12}^2 \right) + \cdots \quad (3)
\]

\( LI_{1 \ldots i} \) is calculated for the lifting task \( j \) on the cumulated frequency of the tasks 1, 2, ..., \( i \). Tasks are numbered in non-increasing order of their individual lifting indices \( LI_i \). Generally, composite \( CLI \leq 1 \) is considered to be acceptable.

For a station load consisting of tasks 6 and 7, we get \( LI_1 = 0.98 \) and \( LI_2 = 0.86 \) as explained above as well as \( LI_{12} = 0.99 \), which corresponds to two lifts of 15 kg in 63 seconds, so that the composite index \( CLI \) amounts to 1.11. Usually, this work load is considered unacceptable.

Similar Methods. Several other methods are constructed according to the logics of the revised NIOSH lifting equation, e.g., the Siemens method (Bokranz and Landau, 2006). Additionally, the Siemens lifting index takes into account \( FI \), a factor that is dependent on demographic characteristics and fitness of the worker:

\[
LI = \frac{\text{Load weight}}{\text{Recommended weight limit}} = \frac{\text{Load weight}}{FI \cdot FM \cdot TS} \quad (4)
\]

Table 1

<table>
<thead>
<tr>
<th>TaskNo.</th>
<th>Task time (seconds)</th>
<th>Actions</th>
<th>Posture</th>
<th>Average force, % of max force capacity (MFC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>8</td>
<td>Hand grip (wide)</td>
<td>20%</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>2</td>
<td>Elbow flexion &gt; 60°</td>
<td>5%</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>5</td>
<td>Elbow flexion &gt; 60°</td>
<td>Insignificant</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>6</td>
<td>Hand grip (wide)</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>5</td>
<td>Neutral posture</td>
<td>1 lifting of 17 kg (avg. force of 70%)</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2</td>
<td>Neutral posture</td>
<td>1 lifting of 15 kg (avg. force of 40%)</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Frequency: lifts/min</th>
<th>&lt;0.2</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>0.85</td>
<td>0.81</td>
<td>0.75</td>
<td>0.65</td>
<td>0.55</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Example of a precedence graph.
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